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Research article

Onshore wind farms do not affect global wind speeds or patterns

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A R T I C L E I N F O

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A B S T R A C T

The proportion of global electricity generated by wind is increasing. There are concerns that onshore wind farms may affect local winds and/or patterns, with impacts on local ecosystems. Global-scale evaluations of these impacts are lacking. To investigate this issue, we used TerraClimate and ERA5 datasets covering the years 1980–1999 to judge the impact of onshore wind farms on wind speeds (at 10 m and 100 m elevations) and their distribution patterns. Winds were compared in two periods approximately representing periods without (1980–1999) and with (2001–2020) large-scale wind farms in existence. The TerraClimate dataset shows that 10 m wind speeds decreased at wind farm locations, while the wind speed distribution patterns did not change significantly. However, in the densest wind farm areas, the 10 m wind speeds actually increased. Analysis of the ERA5 data showed no significant changes in 10 m and 100 m wind speeds or distribution patterns at wind farm locations. The influence of wind farms on local and global wind speeds was slight and far less than that of oceanic/atmospheric oscillations. In the long term, the potential for onshore wind farms to reduce global wind speeds or affect their distribution patterns is very small.

1. Introduction

At present, most countries are trying to reduce their demand for fossil-fuel energy and wind energy is accounting for an increasing proportion of the global energy supply. Under the IEA's Net Zero by 2050 scenario, annual growth rates in wind energy would need to be even greater, reaching 160 GW by 2025 and then 280 GW by 2030, which is three times the capacity installed in 2020 [1]. The impact of wind farms on global wind speed is mainly reflected in two aspects. First, wind turbines convert wind energy into electric energy, which reduces local wind speeds. There are concerns that building large numbers of onshore wind farms will reduce local wind speeds [2–7], which will harm the development of the wind energy industry [2,8,9]. Declines in local wind speeds may affect eutrophication [10], water evaporation, hydrological cycles [11], hydraulic cycles, and air pollutants [12]. Moreover, the operation of wind turbines will affect local atmospheric circulation by affecting wind speed and direction, which may affect the local and even global climate [13]. Therefore, there is increasing attention on the influence of onshore wind farms on wind speed. Wind speed measurements and climate models show that onshore wind farms will indeed affect local wind speed, causing it to decrease in areas 6–30 km downwind [14,15]. These studies have helped to increase our understanding of the impacts of onshore wind farms on global climate change. At the same time, they have aggravated concerns about the rapid increases in onshore wind farms [16]. Due to the high costs of field studies, it is difficult to judge the impact of onshore wind farms on wind speed at the global scale using observed data. It would be cheaper and more effective to study this issue using global climate datasets or models; however, at present, such research is

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lacking. Furthermore, regional differences in this effect remain unknown. To study this effect, we used the TerraClimate and ERA5 datasets to determine wind speed differences at 10 m and 100 m elevations before and after onshore wind farm construction. The research objectives of this paper were to determine.

(1) Whether onshore wind farms will reduce global wind speeds at 10 m and 100 m elevations; and
(2) Whether onshore wind farms will affect the spatial distribution of global wind speeds at these elevations.

2. Data sources

At present, field observations or climate models are mainly used to analyze the impacts of onshore wind farms on local climate [17, 18]. Our purpose was to evaluate the impact of onshore wind farms on global wind speed, so wind speed data were required that had global coverage, were continuous, and were available for periods before and after wind farm construction. The wind speed data used in this paper were obtained from the TerraClimate and ERA5 datasets. TerraClimate includes monthly climate and climatic water balance data for global terrestrial surfaces from 1958 to 2020. TerraClimate uses climatically aided interpolation, combining high-spatial-resolution climatological normal from the WorldClim dataset with coarser-spatial-resolution but time-varying data from the CRU Ts4.0 and Japanese 55-year Reanalysis (JRA55) datasets [19]. The 10 m wind speed data had a monthly temporal resolution and a ~4 km (1/24°) spatial resolution.

ERA5 is the fifth-generation European Centre for Medium-range Weather Forecasts (ECMWF) reanalysis dataset of global climate and weather for the past 4 to 7 decades. The reanalysis combines model data with observations from across the world into a globally complete and consistent dataset based on the laws of physics. The dataset does not have the requirement to issue timely forecasts, so there is more time to collect observations and, when going further back in time, to allow for the inclusion of improved versions of the original observations, all of which benefit the quality of the reanalysis product [20]. ERA5 monthly average wind speed data from 1980 to 1999 was used in this paper, including the average wind speed at 10 m and the 100 m *u*- and *v*-components of the wind. The spatial resolution of this data is 0.25° × 0.25°.

Onshore wind turbine location data were obtained from Ref. [21]. The spatial distribution of wind turbines is shown in Fig. 1.

3. Methods

3.1. Evaluation of trend slopes and significance

Trend analysis is a commonly used mathematical method that uses statistics to form regression equations based on the correlations between dependent and independent variables. It can predict changes in the dependent variables according to the slope of a regression equation [22]. To evaluate the direction and significance of wind speed trends, their slopes (a) and p-values (p) were calculated for six trend classes [23]:

N3: significant negative trend ($a < 0$ and $p \leq 0.05$, $a = a_b$ or a_a).
N2: non-significant negative trend ($a < 0$ and $0.05 < p \leq 0.1$, $a = a_b$ or a_a).
N1: no trend with negative tendency ($a < 0$ and $p > 0.1$, $a = a_b$ or a_a).
P1: no trend with positive tendency ($a > 0$ and $p > 0.1$, $a = a_b$ or a_a).
P2: non-significant positive trend ($a > 0$ and $0.05 < p \leq 0.1$, $a = a_b$ or a_a).

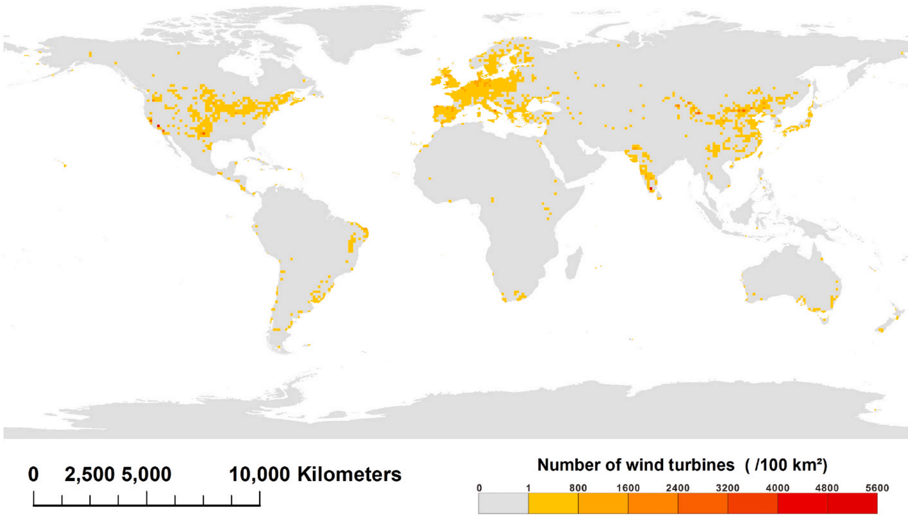

Fig. 1. Global distribution of onshore wind turbines.

P3: significant positive trend ($a > 0$ and $p \le 0.05$, $a = a_b$ or a_a).

Where a is the slope of the linear model, where $a < 0$ indicates a decreasing trend and $a > 0$ indicates an increasing trend. As global wind farm construction developed rapidly after 2000 [24], a_b is the linear trend in wind speed from 1980 to 1999 (before most wind farms were built) and a_a is the linear trend from 2001 to 2020 (after most wind farms were built)

3.2. Moran index

In addition to judging wind speed trends and significance at wind farms, it is also necessary to judge whether wind farms affect the spatial distribution of wind speeds. We use the global Moran index and local Moran index to judge this. The Moran index is an analysis method of spatial autocorrelation, which is used to analyze the dependence of variables in a distribution area and an index showing its spatial autocorrelation, including the local Moran index and global Moran index. The calculation of global Moran index is shown in formula (1) [25]:

$$I = \frac{n}{S_0} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}(y_i - \bar{y})(y_j - \bar{y})}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \tag{1}$$

Where $S_0 = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}$, n is the total number of pixels, y_i and y_j represent the attribute values of the ith and jth pixels, respectively, $\bar{y}$ is the average of all pixel attribute values, and w_{ij} is a spatial weight value, which indicates the adjacent relationship between the i^{th} area and the j^{th} area. If these areas are adjacent, then $w_{ij} = 1$; otherwise, $w_{ij} = 0$.

The value range of the global Moran index is [−1,1], which is used to describe whether there is spatial autocorrelation in a region. Values between [−1,0] mean that the variables have a negative spatial correlation in the region; smaller values indicate a greater spatial difference. Values between (0,1] indicate that the variable has a positive spatial correlation in the region; larger values indicate a more obvious spatial correlation. A value of 0 indicates that the distribution of variables in the region area is random [25].

The local Moran index is used to analyze the influence of onshore wind farms on local wind speeds. Local Moran index values that pass the significance test ($p \le 0.05$) have four output modes: high value (HH) clustering, low value (LL) clustering, abnormal values (HL), where a high value is mainly surrounded by low values, and abnormal values (LH), where a low value is mainly surrounded by high values [25,26]. In this study, the HH and LL modes represent spatial agglomerations of wind speeds with high and low values, respectively, at the centre. The HL mode represents an abnormal wind speed value with a high value mainly surrounded by low values. Finally, the LH mode represents a wind speed with a low value mainly surrounded by high values.

4. Results

4.1. Trends in 10 m wind speeds

Fig. 2a shows the wind speed trend before wind farm construction (1980–1999) according to ERA5 data. As can be seen from

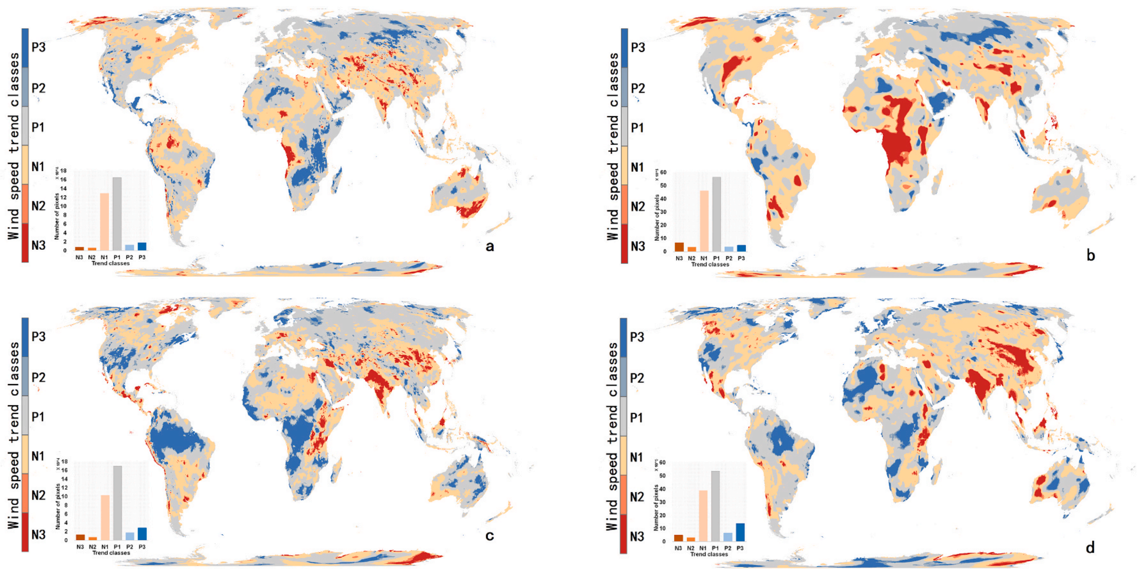

Fig. 2. Global wind speed trend classes: a) 1980–1999 (ERA5 10 m dataset), b) 1980–1999 (TerraClimate 10 m dataset), c) 2001–2020 (ERA5 10 m dataset) and d) 2001–2020 (TerraClimate 10 m dataset).

Fig. 2a, the global 10 m wind speed did not fluctuate significantly. According to our statistics, the wind speeds in 92.5% of the world's regions did not significantly increase or decrease (N1, N2, P1, P2). Of these, insignificantly decreasing trends comprised 40.0% (N1, N2) and insignificantly increasing trends comprised 52.5% (P1, P2). Regions with significantly increased wind speeds accounted for 5.3% of the global land area, and regions with significantly decreased wind speeds accounted for 2.2%. Similarly, we calculated the trends in wind speed classes at wind turbine locations from 1980 to 1999 (Fig. 3a). The wind speeds at 97.9% of the wind turbines did not significantly increase or decrease areas (N1, N2, P1, P2), of which the insignificantly decreasing trends comprised 40.6% (N1, N2) and the insignificantly increasing trends comprised 57.3% (P1, P2). Areas with significantly increased wind speeds account for 1.3% of the global wind turbine distribution area, while areas with significantly decreased wind speeds account for 0.8%. The proportion of significant changes of wind speed shows that before the large-scale construction of wind farms, the 10 m wind speeds were more stable at wind farm locations than in other areas.

Similarly, we used TerraClimate data from 1980 to 1999 to calculate the wind speed trend before wind farm construction (Fig. 2b). Fig. 2b shows that the global 10 m wind speeds did not significantly increase or decrease. Some 90.4% of regional wind speeds did not significantly increase or decrease, of which 40.9% (N1, N2) had insignificant decreases and 49.5% (P1, P2) had insignificant increases. Areas with significantly increased wind speeds account for 4.0% of the global land area, while areas with significantly decreased wind speeds account for 5.6%. Similarly, we used TerraClimate data to calculate the wind speed trend classes at wind farm locations from 1980 to 1999 (Fig. 3b). These were close to the global trend, with 93.4% of regional wind speeds not being significantly higher or lower, of which 56.3% (N1, N2) had insignificant decreases and 37.0% (P1, P2) had insignificant increases. Significantly higher wind speeds were found in 0.2% of the future wind farm areas, while significantly lower wind speeds were found in 6.4%.

The ERA5 and TerraClimate 10 m wind speed data show that global wind speeds were generally stable from 1980 to 1999. Although these datasets provided somewhat different results, both indicate that wind speeds in more than 90% of the world did not increase or decrease, and that wind farm locations had similar wind speed trends to the global trend.

To judge the impact of wind farms on 10 m wind speeds around the world, we calculated the wind speed trend classes after wind farm construction (2001–2020) using ERA5 data (Figs. 2c and 3c). Fig. 2c shows that although the spatial distribution of trend classes was different from that in 1980–1999, there were no significant changes in areas where wind speeds significantly increased or decreased. Fig. 3c shows that the wind speed trends at wind farm locations were close to the global trend. There were no significant changes in wind speed; hence, wind farms did not significantly influence 10 m wind speeds.

Similarly, using TerraClimate data, we calculated the 10 m wind speed changes after the start of wind farm construction. The results are shown in Figs. 2d and 3d. Fig. 2d shows that the global wind speed was still stable from 2001 to 2020, but the area with significant increases in wind speed was greater than that from 1980 to 1999. The proportion of global land area with significant increases in wind speed increased from 4.0% to 11.5%, while that with significant decreases in wind speed decreased from 5.6% to 4.1%. It is worth noting that the area with wind increases or declines was almost unchanged compared with 1980–1999 (Figs. 2d and 3d). Hence, wind speeds in wind farm areas did not increase or decrease significantly.

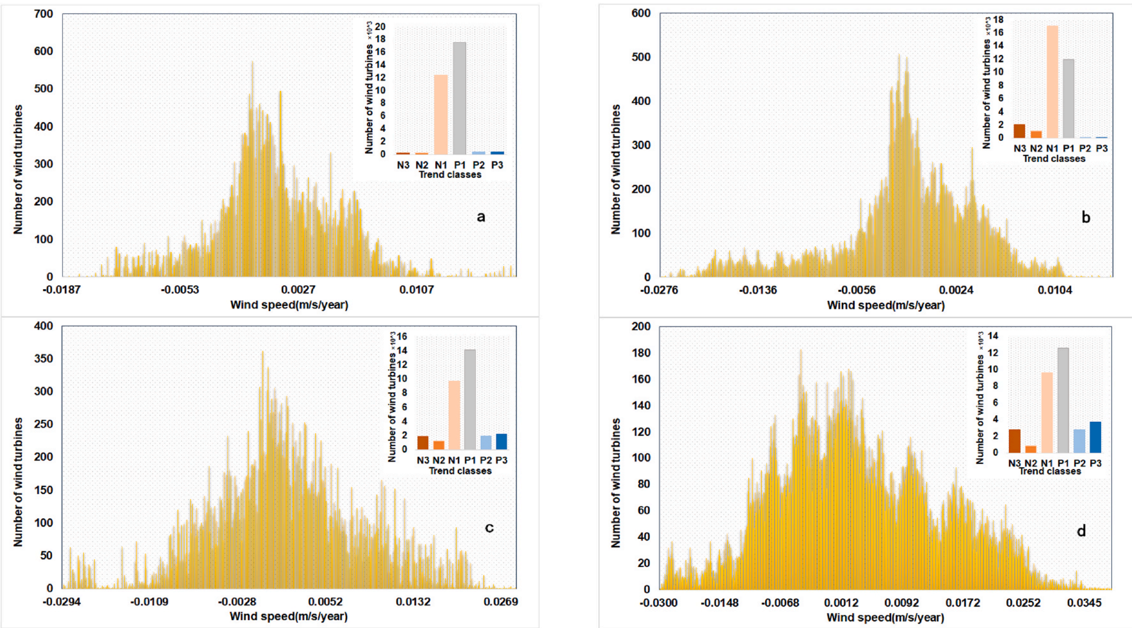

Fig. 3. Wind speed trend classes at wind farm locations: a) 1980–1999 (ERA5 10 m dataset), b) 1980–1999 (TerraClimate 10 m dataset), c) 2001–2020 (ERA5 10 m dataset) and d) 2001–2020 (TerraClimate 10 m dataset).

4.2. Trends in 100 m wind speeds

TerraClimate data does not include 100 m wind speeds while ERA5 data does, so the changes in 100 m wind speeds were determined by analysing ERA5 data. Fig. 4a shows that from 1980 to 1999 (before wind farm construction), there was no significant increase or decrease in global 100 m wind speeds. The wind speeds in 94.0% of the regions did not change significantly (N1, N2, P1, P2), of 47.0% of regions (N1, N2) had insignificant decreases and 47.0% (P1, P2) had insignificant increases. Regions with significant increases in wind speed accounted for 3.3% of the global land area, while those with significant decreases accounted for 2.7%. Fig. 5a shows that 96.5% of regional wind speeds did not change significantly (N1, N2, P1, P2); of these regions, 64.6% (N1, N2) had insignificant decreases and 31.9% (P1, P2) had insignificant increases. As shown in Fig. 4b, from 2001 to 2020, the wind speeds in 91.1% of the regions did not change significantly (N1, N2, P1, P2); of these regions, 40.5% (N1, N2) had insignificant decreases and 50.6% (P1, P2) had insignificant increases. Regions with significantly increased wind speeds accounted for 4.0% of the global land area, while those with significant decreases accounted for 4.9%. As shown in Fig. 5b and 93.7% of the regional wind speeds in wind farm areas did not change significantly (N1, N2, P1, P2); of these regions, 29.7% (N1, N2) had insignificant decreases and 64.0% (P1, P2) had insignificant increases.

It can be seen that the 100 m wind speed trends in wind farm areas were close to the global trend, and 91% of wind farm areas were mainly stable, which further proves that the wind farm will not reduce the 100 m wind speed.

4.3. Spatial distribution of wind speeds

4.3.1. Changes in the global Moran index

The impact of wind farms on the global Moran index may differ in different climate zones. To judge whether wind farms affected the spatial distribution of wind speeds in typical climatic zones, we selected three areas with dense wind farms and one control area. These four areas had similar latitudes (Fig. 6) and were parts of North America (NA; temperate continental climate), parts of Europe (EU; temperate maritime climate), Control Area (CA; temperate continental climate) and parts of East Asia (EA; medium-latitude monsoon climate).

We calculated the global Moran indexes of 10 m and 100 m wind speeds in these four regions from 1980 to 2020. As the changes of wind speed at sea is not the focus of this paper, we only calculate the global Moran indexes of land areas in four regions, and compared them with the global Moran index (Fig. 7).

It can be seen from Fig. 7 that the global Moran index of wind speeds at 100 m and 10 m is close to 1, which indicates that the wind speeds in the above areas are very obviously spatially correlated. In particular, the 10 m wind speed TerraClimate and ERA5 data show that the global Moran index of wind speed has no obvious change, and the spatial distribution differences are not obvious (Fig. 7a and b).

As can be seen from Fig. 7c, the global Moran index of 100 m wind speeds fluctuates more than that of 10 m wind speeds, but there are no obvious differences between the indexes of the wind farm and control areas. After 2000, when centralized construction of wind farms began, the global Moran index of the wind farm areas did not change significantly. Hence, wind farms did not significantly change the spatial distribution patterns of 10 m or 100 m wind speeds.

4.3.2. Changes in local Moran indexes

To further judge the change in the spatial distribution of wind speeds after wind farm construction, we calculated the global average wind speeds in 1980–1999 and 2001–2020 using ERA5 and TerraClimate data. We also calculated the local Moran index of wind speed (Fig. 8a to f). Fig. 8 shows that although there are some differences in the spatial aggregation distributions of wind speeds calculated from ERA5 and TerraClimate data, there is almost no difference in either 10 m or 100 m wind speeds between the two time periods. It can be seen that the global wind speed distribution is very stable and, after wind farm construction, the spatial distribution of global wind speeds was almost unchanged.

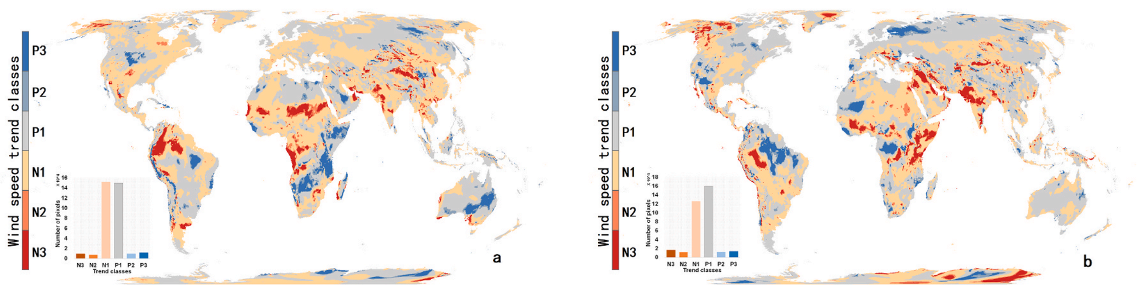

Fig. 4. Global wind speed trend classes: a) 1980–1999 (ERA5 100 m dataset) and b) 2001–2020 (ERA5 100 m dataset).

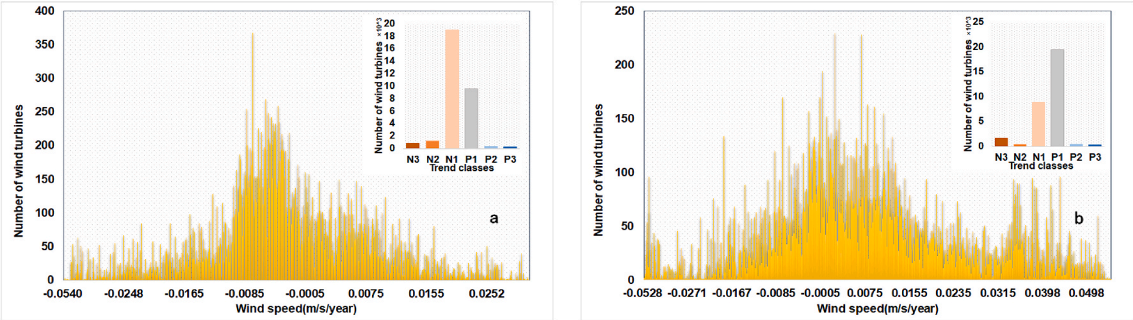

Fig. 5. Wind speed trend classes at wind farm locations: a) 1980–1999 (ERA5 100 m dataset) and b) 2001–2020 (ERA5 100 m dataset).

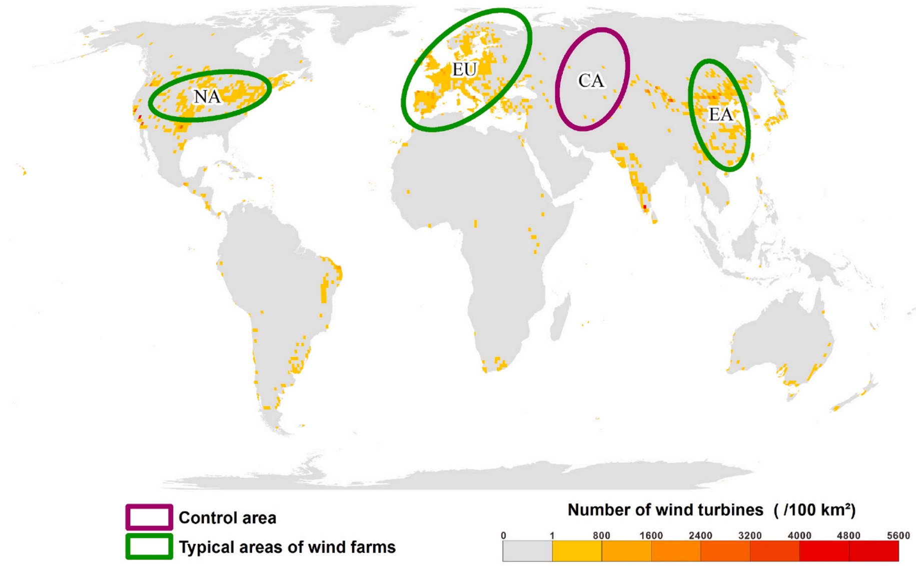

Fig. 6. Locations of typical wind farm areas and control area.

5. Discussion

5.1. Comparison with current research

Existing research shows that wind farms decrease local wind speeds [14,15]. The wake propagation distance of large onshore wind farms is concentrated in the range of 10–30 km [15,27], so wind speed changes over longer distances are very weak. Some 90% of wind farms with significant wind speed decreases are concentrated in China and India. Therefore, if only China and India are studied, it may be concluded that wind farms decrease wind speeds [14]. If wind farm areas in Britain, Denmark, Sweden or Japan are studied, it may appear that wind farms increase wind speeds because, as shown in Fig. 4, more than 90% of wind farm locations with increased wind speeds are concentrated in these countries.

5.2. Can onshore wind farms change the global wind speed?

The above results show that the wind speed distribution in onshore wind farm locations did not change significantly after wind farms were constructed. By analyzing data measured at weather stations around the world, it is found that variations in near-surface wind are driven by internal decadal oceanic/atmospheric oscillations, rather than by vegetation growth and/or urbanization, as has been hypothesized previously [28]. Therefore, although onshore wind farms can reduce local wind speeds, their influence is insufficient to overcome the influence of oceanic/atmosphere oscillations, nor do they affect global 10 m or 100 m wind speed distributions.

5.3. Research limitations

The robustness of an analysis depends on its scope, data and process. If wind speed data with different date ranges are selected,

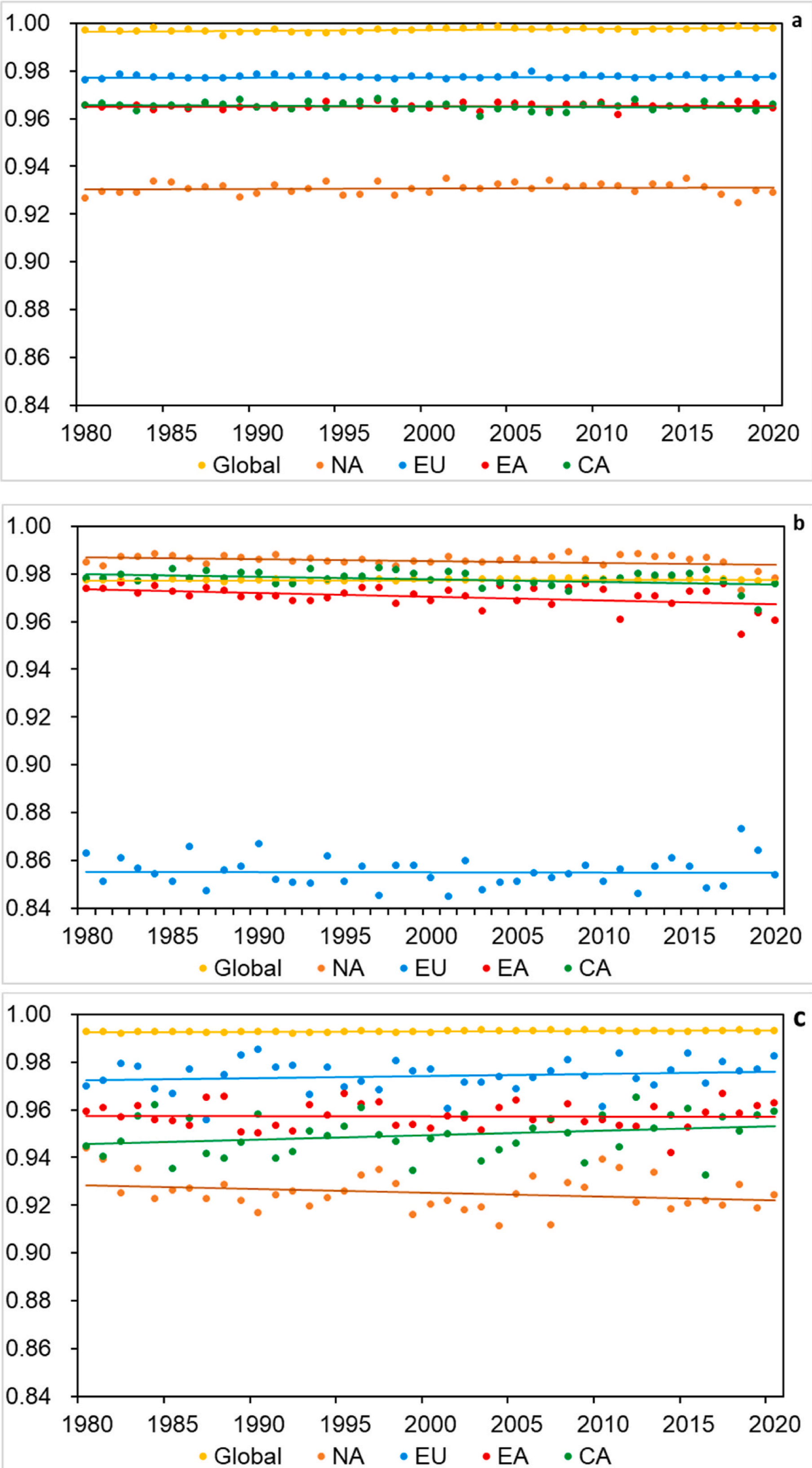

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Fig. 7. Global Moran indexes of wind speeds in the three wind farm areas and control area. Wind speed data is a) 10 m ERA5, b) 10 m TerraClimate and c) 100 m ERA5.

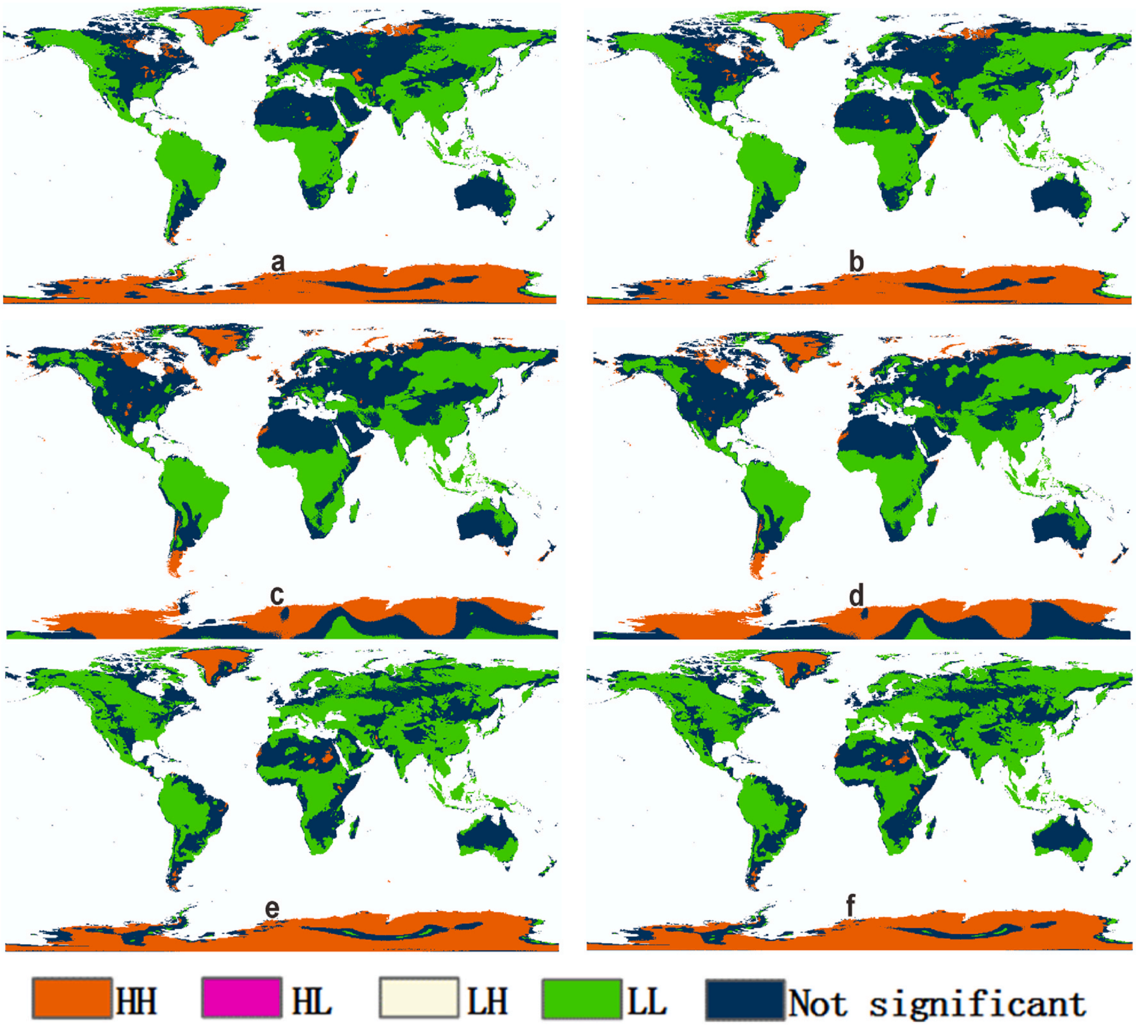

Fig. 8. Global distribution of the Moran index in the period 1980–1999 (left column) and 2001–2020 (right columns) based on a, b) ERA5 10 m wind speeds; c, d) TerraClimate 10 m wind speeds; and e, f) ERA5 100 m wind speeds.

different areas of significant global wind speed change may be identified. With sufficient sample numbers and significance tests in this paper, although this difference will not change our results, our result is a description of wind speed change from 1980 to 2020, which does not represent the trend of wind speed change in the future. To judge whether land-based wind farms will affect global wind speeds in the next few decades, it is necessary to consider the results of this paper and to consider the predictive models of climate and wind farm development.

5.4. Future research

The influence of onshore wind farms on local climate is quite clear. Wind farms may affect local economic development and crop growth. One potential externality that has been considered in the economics literature is the effect of wind farms on crop outcome due to "microclimate" effects. There are also studies that took an economic approach and analyzed county-level data to find that onshore wind farms increase crop yields [29–31] It is necessary to use econometric methods to evaluate the impact of onshore wind farms on the local climate, economy and cropping. In this paper, we only evaluated the impact of onshore wind farms on global wind speeds, while their impacts on other climatic elements remain unclear. In future, we will determine whether onshore wind farms have significant impacts on meteorological factors such as global temperature and precipitation. Obtaining the global trends in these factors will form a basis for judging the economic impacts of onshore wind farms at the local and even global scales.

6. Conclusions

Onshore wind farms have a very limited influence on wind speeds. Although our analysis is based on 2020 data, the number of onshore wind farms will increase very rapidly in future. However, the potential for wind farms to decrease global wind speeds and alter their distribution is very small. At present, the density of onshore wind turbines in Denmark and Germany is 0.02 per km^2, which is almost at the maximum limit. Yet, our results indicate no changes in the spatial distributions of wind speeds in these areas due to wind farm construction; indeed, wind speeds in these areas have increased significantly. From the perspective of energy conversion, wind turbines cannot increase wind speeds during operation, so these increases are more likely caused by oceanic and atmospheric oscillations. Of course, we cannot rule out that other factors may have caused changes in wind speed at onshore wind farm locations. Compared with other factors that affect land wind speeds, the impact of onshore wind farms is very slight.

Author contribution statement

Guoqing Li: Conceived and designed the experiments; Wrote the paper. Chuncheng Yan: Performed the experiments; Contributed reagents, materials, analysis tools or data. Haipeng Wu: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no competing interests.

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